The California Seafloor and Coastal Mapping Program - Providing science and geospatial data for California's State Waters

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Abstract

The California Seafloor and Coastal Mapping Program (CSCMP) is a collaborative effort to develop comprehensive bathymetric, geologic, and habitat maps and data for California's State Waters. CSCMP began in 2007 when the California Ocean Protection Council (OPC) and the National Oceanic and Atmospheric Administration (NOAA) allocated funding for high-resolution bathymetric mapping, largely to support the California Marine Life Protection Act and to update nautical charts. Collaboration and support from the U.S. Geological Survey and other partners has led to development and dissemination of one of the world's largest seafloor-mapping datasets. CSCMP provides essential science and data for ocean and coastal management, stimulates and enables research, and raises public education and awareness of coastal and ocean issues. Specific applications include:

- Delineation and designation of marine protected areas
- Characterization and modeling of benthic habitats and ecosystems
- Updating nautical charts
- Earthquake hazard assessments
- Tsunami hazard assessments
- Planning offshore infrastructure
- Providing baselines for monitoring change
- Input to models of sediment transport, coastal erosion, and coastal flooding
- Regional sediment management
- Understanding coastal aquifers

- Providing geospatial data for emergency response

1. Introduction

The California Coastal and Seafloor Mapping Program (CSCMP) is an ambitious collaborative effort to develop comprehensive bathymetric, habitat, and geologic maps and data for California's State Waters, which extend from the shoreline to 5.56 km (3 nm) offshore. CSCMP began in November 2007, when the California Ocean Protection Council (OPC) allocated bond funds for high-resolution bathymetric mapping, largely to support the California Marine Life Protection Act Initiative and the delineation and monitoring of marine protected areas. Significant support followed from the National Oceanic and Atmospheric Administration (NOAA) Office and Coast Survey for updating nautical charts, and from the U.S. Geological Survey (USGS) for constraining geologic hazard assessments and models of coastal evolution. Together with contributions from many other partners, CSCMP activities have led to development of one of the world's most large-scale, comprehensive, seafloor-mapping datasets, providing essential information for ocean and coastal management.

The first several years of work and about 95 percent of CSCMP funding was focused on data acquisition, and it was not until late 2014, when significant products and publications became available, that outreach efforts became a higher priority. The objective of this paper is to document the case history of CSCMP, in particular the numerous applications of CSCMP maps and data. The goal is to promote the value of seafloor and coastal mapping, and to provide a model for developing comparable efforts elsewhere. A progress report on CSCMP's major components is outlined below, and described in U.S. Geological Survey (2016).

2. Data Acquisition

2.1 High-resolution bathymetry and backscatter

California's mainland State Waters extend ~1,350 km from the northern border with Oregon to the southern border with Mexico (Fig. 1). Prior to CSCMP, high-resolution bathymetric mapping data were available for just 20 percent of mainland State Waters, and were virtually nonexistent for State Waters bounding California's offshore islands. Since CSCMP began, mapping using multibeam and interferometric sonar sensors has been completed in State Waters along all of California's mainland and surrounding Santa Catalina and San Nicolas

Islands, and is partially complete around most of California's other offshore islands. Fugro (a private contractor), the California State University at Monterey Bay Seafloor Mapping Lab (CSUMB-SFML), and the USGS conducted this mapping, with primary funding from OPC and NOAA. This ship-based mapping typically extends from the 10 m isobath to the outer edge of State Waters. Seafloor at depths of 0 to 10 m is generally not mapped from boats for safety reasons, but this zone has been partially covered in southern California by bathymetric lidar (Light Detection and Ranging) data collected by the U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program (U.S. Army Corps of Engineers, 2016). Small areas in shallow waters have also been mapped using the CSUMB-SFML R/V Kelpfly, an interferometric sonar mounted on a jet ski (data available at California State University at Monterey Bay—Seafloor Mapping Lab, 2016). Merged CSCMP bathymetric data and onshore coastal lidar data are available through the 2013 NOAA Coastal California TopoBathy Merge Project (National Oceanic and Atmospheric Administration, 2016a). The CSUMB-SFML Data Library also serves CSCMP bathymetric data, preliminary backscatter imagery, and several other thematic layers. U.S. Geological Survey (2016) is also serving digital bathymetric data and merged and processed backscatter data, as well as pdf maps, with all CSCMP map and data publications (see 3 below).

2.2 Ground-truth surveying

The remotely sensed CSCMP bathymetric sonar data have been "ground truthed" in all of California's mainland State Waters by the USGS (with primary funding from USGS and OPC) using a camera sled mounted with two or three digital video cameras (oblique and vertical orientations) and an 8-megapixel still camera. The camera data were transmitted via a conducting tow cable to shipboard video monitors and real-time geological and biological observations were recorded into a database for a 10-second observation period once every minute. Geologic observations include composition (i.e., rock, sand), complexity, and local slope. Biological observations include biological complexity and coverage, and the presence of a predetermined set of flora and fauna. Ground-truth surveys were strategically designed to visually inspect areas representative of the full range of bottom hardness and rugosity in different map areas, and transitions between such areas. All ground-truth imagery data are available at Golden and Cochrane (2013), an interactive web portal hosting more than 550 km of trackline video and

87,000 photographs.

2.3 Seismic-reflection profiling

Seismic-reflection profiling provides the information to understand subsurface geologic framework, including distribution and thickness of unconsolidated sediment, the locations of active faults, folds, slumps, landslides, and gas-saturated zones, and the structure of offshore portions of coastal aquifers. The CSCMP effort is using high-resolution, single-channel seismic profiles as well as archived, multichannel, seismic-reflection profiles from the USGS National Archive of Marine Seismic Surveys (Triezenberg et al., 2016). Since CSCMP began in 2007, USGS has collected new high-resolution seismic profiles at approximately 1 km line spacing for about 65 percent of California's mainland State Waters. Most of these data are now publicly available at Beeson et al. (2016), Johnson et al. (2017b), and Sliter et al. (2008, 2009, 2013, 2016).

2.4 Coastal Lidar

Topographic lidar data have been collected for the California coast (including San Francisco Bay) from the shoreline to 500 m onshore, covering 9,788 km^2. This effort was funded by OPC, NOAA, and the USGS, and made possible by a larger partnership that also included the California Coastal Conservancy, Army Corps of Engineers, and industry partners Dewberry and Fugro EarthData, Inc. The lidar data are currently available online for the entire coastline, along with digital elevation models and aerial photographs. All of these data sets can be downloaded from NOAA's Digital Coast (National Oceanic and Atmospheric Administration, 2016).

3. Map and Data Publications

USGS and OPC have supported development of peer-reviewed map and datasets for California's mainland State Waters (e.g., Figs. 1, 2; Cochrane et al., 2015; Johnson et al., 2013; U.S. Geological Survey, 2016). The purpose of these publications is to present the fully processed, highest quality data, and to add value to the basic data through geospatial analysis and interpretation of habitats, geology, and geomorphology. Creating easy to use web interfaces and providing information in a range of formats in order to maximize map/data accessibility and availability is a priority. The goal is to serve a large, diverse audience, including all levels of the resource management and interest community, ranging from senior GIS analysts in large agencies, to local governments with limited resources, to non-governmental organizations, and concerned citizens and the private sector. The map and data publications are also intended to support coastal and marine research on multiple levels, to provide educational material, and to enhance public awareness of coastal and ocean issues.

Twenty-five USGS map and datasets have been published as of February, 2017. These publications cover about 32 percent of California's mainland State Waters in two regions (Fig. 1), from Hueneme Canyon east to Point Conception in the Santa Barbara Channel, and from Monterey north to Salt Point (northern Sonoma County) in central and northern California. Each map and data publication represents a large collaborative effort (42 co-authors have been involved) representing federal, state, academic, and private-sector partners.

Each publication contains 10 downloadable pdf map sheets, at 1:24,000 scale (unless stated otherwise), for a selected coastal map area that typically traverses about 17 km of linear coast (Fig. 2). Sheets 1 and 2 in each map set are two different displays (color and grayscale) of shaded-relief bathymetry. Sheet 3 displays processed backscatter intensity, which provides a general indication of seafloor hardness and sediment type. Both bathymetry and backscatter maps commonly require complex merging of multiple datasets. Sheet 4 highlights perspective views of the bathymetry and backscatter, commonly combined with ground-truth or seismic-reflection data, that highlight and interpret important and (or) noteworthy seafloor features in the map area (e.g., rocky habitat, submarine canyons, fault scarps, seafloor slumps, sand waves, rippled scour depressions).

Sheet 6 in each map set (Fig. 2) presents images from ground-truth surveys, collected to validate geological and biological interpretations of the sonar data shown in sheets 1, 2, and 3. Sheet 5 is a "Seafloor Character" map, which is a video supervised numerical classification of the seafloor on the basis of rugosity (ruggedness), and backscatter intensity, which is subsequently divided into depth and slope classes (Cochrane, 2008). Sheet 7 is a map of Potential Habitats, which are delineated on the basis of substrate type, geomorphology, seafloor process, and other attributes that may provide a habitat for a specific species or assemblage of organisms (Greene et al., 1999).

Sheet 8 in each map set (Fig. 2) is a compilation of representative seismic-reflection profiles (typically 10 to 12) from a map area, providing information on subsurface stratigraphy and structure. Sheet 9 shows the distribution and thickness of young sediment (1:50,000 scale), deposited over the last about 21,000 years, during the post-Last Glacial Maximum sea-level rise (Stanford et al., 2011). Sheet 9 also includes broader regional maps (1:200,000 to 250,000 scale) of sediment distribution and thickness, as well as a regional map showing offshore faults and recorded earthquakes. Sheet 10 is a seamless geologic and geomorphic map that merges onshore geologic mapping (updated and compiled by the California Geological Survey) and new offshore geologic mapping that is based on integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples from the usSEABED database (Reid et al., 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8). To create the seamless geologic maps, the shallow 0- to 10-m depth zones are interpreted on the basis of limited bathymetric lidar coverage, multiple generations of aerial photographs served by the California Coastal Records Project (2016), Esri DigitalGlobe (2016), and Google Earth. The sheet 10 geologic maps show different marine sediment types, rock units, areas of thin sediment cover that could represent transitional habits, scour depressions, nearshore bars, debris lobes, sand waves, submarine landslides, faults and folds, pockmarks and asphalt mounds, trawl marks, and many other geologic and geomorphic features.

Several map and data publications from the Santa Barbara Channel map areas (from Refugio Beach to Hueneme Canyon) also include additional thematic sheets that highlight phenomena such as detailed geomorphology of Hueneme submarine canyon, the predicted distribution of benthic macro-invertebrates, and natural offshore hydrocarbon seepages.

Each map and data publication also includes an explanatory pamphlet and a set of digital GIS data layers (about 15 to 25 per map area) that are published separately in a comprehensive statewide USGS CSCMP data catalog (Golden, 2016). Web services have been added for all published GIS layers, providing enhanced discoverability and allowing for easier access to multi-resolution basemaps. Web services allow data to be delivered and discovered by any web client, including professional desktops, web browsers, mobile clients, smartphones, and other information technology. This also gives users the ability to leverage web map services as digital basemaps onto which they can layer their own GIS information and tasks.

4. CSCMP Applications

CSCMP embraces the philosophy of *map once, use many times*, and the extent to which the same maps and data can be used for a large number of management and research applications is remarkable. In outreach efforts (see below), we also stress that y*ou can't manage it, monitor it, or model it if you don't know what the "it" is. Seafloor mapping provides the "it*." Some of the many important management and research applications are discussed below.

4.1 Delineation and designation of California's Marine Protected Areas

California's coastal network includes 119 marine protected areas (MPAs) and 5 state marine recreational management areas that cover approximately 2,207 km^2 (about 16 percent) of State Waters (California Department of Fish and Wildlife, 2016). Delineation of this network was a complex process that depended on a range of physical, biological, geographic, and social data that included (when and where available) CSCMP bathymetry and derived habitat maps (Gleason et al., 2010; Saarman et al., 2013). Young and Carr (2015a) further discuss how the CSCMP mapping data is and can be used to assess habitat representation across MPAs with implications for the effective spatial design of monitoring strategies.

4.2 Characterization and modeling of benthic habitats and ecosystems

Figure 3 highlights the diversity of benthic habitats in California's State Waters, and there are numerous examples (a few described below) of the utility and value of CSCMP data in defining and modeling such benthic habitats and ecosystems. For the Santa Barbara Channel, Krigsman et al. (2012) combined data from CSCMP seafloor character maps with ground-truth observations to develop predictive models of occurrence for common macro-invertebrate species, validate these models, and map the probability of species occurrence. Young and Carr (2015b) developed species distribution models from CSCMP mapping data to explain and predict the distribution, abundance, and assemblage structure of nearshore temperate reef fishes. Davis et al. (2013) used CSCMP bathymetry and backscatter to document the surprisingly large portion of State Waters seafloor (3.6 %) that consists of rippled scour depressions (RSDs), elongate deposits of coarser-grained sediment with long-wavelength bedforms depressed 40 to 100 cm below the surrounding, elevated, finer-grained sediment-covered seafloor (e.g., Fig. 3). In a companion study, Hallenbeck et al. (2012) described the ecological influence and associated biological communities of RSDs. Greene et al. (2013) combined CSCMP potential habitat maps from offshore San Francisco with similar existing maps in San Francisco Bay to document potential habitats at the mouth of California's largest estuary, emphasizing strong tidal influence and the relationship between geology and ecology.

4.3 Updating NOAA nautical charts

NOAA's Office of Coast Survey is the nation's nautical chartmaker, compiling a catalog of over a thousand charts covering 95,000 miles of shoreline and 3.4 million square nautical miles of waters within the U.S. Exclusive Economic Zone (National Oceanic and Atmospheric Administration, 2016a,b). These charts are updated continually with CSCMP and other new datasets, and have an important role in ensuring commercial and recreational marine safety.

4.4 Earthquake hazard assessments

California is "earthquake country," and the safety and viability of the built environment in the coastal zone relies on accurate earthquake hazard assessments. The USGS provides such assessment with its National Seismic Hazard Maps (U.S. Geological Survey, 2014), which display earthquake ground motions for various probability levels across the United States. These maps have enormous economic impact as they are used in seismic provisions of building codes, insurance rate structures, risk assessments, land-use planning, and other public policy. The regularly updated maps represent the best available science in earthquake hazards, and incorporate data on active faults as potential earthquake sources. Specific information that is factored into the hazard assessments includes fault location, length, connections, dip, slip rate, and earthquake history. Much of the needed information on active faults in California's State Waters can be derived by integration and analysis of CSCMP seismic-reflection and bathymetry/backscatter datasets, as represented on geology/geomorphology maps (Fig. 2, sheets 1, 2, 3, 8, 10). In Figure 2, for example, new CSCMP mapping (sheet 10) based on seismic-reflection data shows that the main strand of the San Andreas fault at Bodega Bay is located 800 m west of its previously mapped position (Johnson et al., 2015a). The San Andreas fault is the boundary between the Pacific and North American tectonic plates and ruptured for about 300 km in a M7.8 earthquake in 1906. An accurate location of its primary strand is essential for forecasting local ground failure and strong ground motions.

In central California, Johnson and Watt (2012), Johnson et al. (2014), and Watt et al. (2015) used CSCMP data to map and document the location, length, connectivity, and slip rate of the Hosgri fault, along with several other active faults proximal to the Pacific Gas and Electric (PG&E) Diablo Canyon nuclear power plant (DCPP, Fig. 4). Earthquake hazard assessment for DCPP, which presently generates about nine percent of California's power, has been contentious, attracting significant scientific and public discussion since DCPP construction began in 1968. New CSCMP data and maps fed research that was used by both the USGS (Field et al., 2013) and Pacific Gas and Electric (2015) for updates to regional and local hazard assessment, the latter publication in partial response to recommendations of the U.S. Nuclear Regulatory Commission (2011) Fukushima Dai-Ichi Near-Term Task Force. On June 20, 2016, PG&E announced that DCPP would be shutting down in 2025, however nuclear wastes will continue to be stored on site for the foreseeable future.

Similar CSCMP seismic-reflection data and geologic/geomorphic maps from the eastern Santa Barbara Channel (Johnson et al. 2013; 2016) provide new information on the location, length, and slip rate of the offshore Pitas Point fault system, which has recently been described as capable of a M7.5 to 8.1 earthquake in the Santa Barbara Channel region (Hubbard et al., 2014; McAuliffe et al., 2015).

4.5 Tsunami hazard assessments

CSCMP bathymetric and coastal topographic data will provide essential input to future, high-resolution tsunami inundation models (e.g., California Geological Survey, 2016). These models are especially important for the northern ~180 km of coastal California (from Cape Mendocino to the Oregon border; Fig. 1), which faces the Cascadia subduction zone. This subduction zone is the boundary between the Juan de Fuca/Gorda and North American tectonic plates, and ruptures about every 500 ± 200 years in one or more earthquakes ranging from M8 to 9.2 (e.g., Frankel and Petersen, 2008) - the last such event occurred in AD 1700 (Satake et al., 2003; Atwater, 2005). Future earthquakes are expected to generate massive tsunamis with enormous coastal geomorphologic and cultural impact, comparable to the devastating 2004 Banda Aceh earthquake in Sumatra (e.g., Paris et al., 2008) and the 2011 Tohuku-Oki earthquake in Japan (e.g., Udo et al., 2012). In addition to providing important inundation-modeling constraints, CSCMP bathymetry and coastal topography will provide an essential baseline for quantifying the geomorphologic change associated with future Cascadia earthquakes and tsunamis (see 4.6, below), including anticipated coseismic coastal subsidence of as much as 1.5

m (Leonard et al., 2004).

CSCMP bathymetry and seismic-reflection data, and geologic-geomorphic maps, also inform hazard assessments by characterizing potential tsunami sources in State Waters. Specifically, this work consists of (1) documenting the size of former submarine landslide bodies and identifying sites of future submarine landslides, and (2) documenting vertical displacement on active faults as a proxy for future coseismic offsets. There are records of a few historical tsunamis generated from local offshore sources that have impacted California. Along the Santa Barbara Channel coast, for example, tsunami run-up for a local earthquake in 1812 reached 4 m (Toppozada et al.,1981; Borrero et al., 2002). Local models in the Santa Barbara Channel suggest tsunami run-ups from 8,000 to 10,000 ybp submarine landslides (Fisher et al., 2004) in the Goleta complex (130 km^2, Fig. 5a) could have reached 10 to 15 m (Greene et al., 2006; Borrero et al., 2002), and at least 8 m of runup has been modeled for offsets on the Ventura-Pitas Point fault (Ryan et al., 2015). Smaller submarine landslides are also present on the continental slope west of the Goleta slide (e.g., the Gaviota slide, parts of the Conception fan; Fig. 5a). East of the Goleta slide, areas of slope-parallel tension cracks, gravitational creep, bulges, and troughs that occur on the slope east of Hueneme Canyon (Fig. 5b) are obvious sites of potential future submarine landslides. CSCMP data have also been used to map large (> 1 km^2) submarine landslides and landslide complexes on the flanks of Hueneme (Fig. 5b; Ritchie et al., 2012) and Monterey (Maier et al., 2016) submarine canyons.

Apart from the Santa Barbara Channel, narrow continental shelves paired with steep slopes that are prone to landsliding occur locally in southern California (Lee et al., 2009), along the Big Sur coast in central California (Fig. 1; Johnson et al., 2015c), and on the southwest flank of Cape Mendocino in northern California (Fig. 1). These three areas are presently not covered by comprehensive CSCMP publications (e.g., Fig. 2).

4.6 Planning offshore infrastructure

Comprehensive seafloor mapping supports a range of decisions regarding offshore leases and siting of offshore infrastructure, including moorings, cables, pipelines, and platforms. Current issues dealing with offshore infrastructure in California’s State Waters involve potential development of renewable energy, desalination, and aquaculture, as well as continuing operation of offshore oil production and drilling platforms. Such issues and many others require information from seafloor bathymetric and geologic maps on seafloor composition and stability.

Seafloor instability is not limited to areas of steep slopes. Figure 6a shows a large area (6.1 km^2) of seafloor failure and debris flows mapped on a 1° slope on the Offshore of Bodega Head and Offshore of Fort Ross map areas (Johnson et al., 2015a,b). Individual lobes within the field are as much as 1,000-m long and 200-m wide, have as much as 4 m of relief above the surrounding smooth seafloor, and are commonly transitional to upslope chutes. Given their morphology and their proximity (about 2 km) to the San Andreas Fault (Fig. 6b), we infer that these debris-flow lobes result from strong ground motions triggered by large earthquakes on the San Andreas Fault. There are many other major active faults along the California coast, including the Cascadia subduction zone north of Cape Mendocino, the Hosgri-San Gregorio fault system in central California, and the Pitas Point fault system in the Santa Barbara Channel, and other large mapped zones of ground failure on the shelf that are reasonably associated with earthquakes occur in Monterey Bay (4.4 km^2; Cochrane et al., 2015) and the western Santa Barbara Channel (> 4 km^2; Johnson et al., 2017). It is highly likely that there are many other similar but unmapped zones of seafloor ground failure or potential ground failure in California's State Waters and adjacent federal waters.

Hydrocarbon fluid escape is common in California's State Waters (e.g., Hornafius et al., 1999) and may also be a factor in destabilizing sediment on the shelf and along the upper slope (Fisher et al. 2005; Greene et al., 2006). Hence, geologic maps showing pockmarks, fields of dense pockmarks, carbonate and asphalt mounds and mats, mud volcanos (Figs. 5b, 7), and other evidence of seafloor hydrocarbon emissions also provide relevant data for siting offshore infrastructure.

California has long-term bans on new leasing for offshore oil and gas development in State (since 1969) and federal (since 1984) waters, but hydrocarbon drilling and production continue offshore California from drilling and production platforms on pre-existing leases. Nine active offshore platforms or artificial islands are located in state and municipal waters, and 23 platforms remain in adjacent federal waters. In the Santa Barbara Channel, Platform Holly (Fig. 5a) oil production is from reservoirs in the South Ellwood anticline (Fig. 7) and operators have proposed significant lease-boundary adjustments to expand drilling along the anticlinal trend (Fig. 7). To inform review of such proposals, CSCMP geologic mapping highlights the local areas above the fold where hydrocarbon seepage has occurred, seismic reflection profiles provide shallow subsurface information on faults, folds, and hydrocarbon-charged rock and sediment, and geologic and geophysical data can be integrated to identify and assess potential local geologic hazards.

Bathymetric, habitat, and geologic maps and data also provide useful information for important pending decisions regarding platform decommissioning, including “rigs to reefs” options, for which knowing the location and abundance of surrounding natural reef habitat is an especially important consideration. For desalination plants, offshore subsurface saltwater intakes are considered desirable because they avoid biological entrainment, but location of such facilities requires information on subsurface geology and on sediment type, thickness, and mobility. CSCMP maps and data can provide the information to identify potential sites, saving local water districts significant resources, however more detailed geologic and subsurface mapping will generally be required for final site evaluation. A proposed desalination facility in Moss Landing utilizing a deep saltwater intake in Monterey Canyon (Fig. 8) is currently using the CSCMP Monterey Canyon and Vicinity map and data sets (Dartnell et al., 2016) in project presentation materials.

4.7 Providing baselines for monitoring change

Given anticipated impacts of climate change, including accelerated sea-level rise and associated coastal erosion and modification, CSCMP high-resolution bathymetry and topography provide essential baselines in time-series analyses for environmental monitoring and change detection. Comprehensive change analysis of California’s shorelines and coastal cliffs was last conducted prior to CSCMP data availability as part of the USGS National Shoreline Change Assessment (Hapke et al., 2006; Hapke and Reid, 2007). CSCMP lidar data will be an essential time stamp for future assessments, and are already being used to develop models of the retreat of California’s coastal cliffs during the 21st century (Limber et al., 2015). Three examples of pre-CSCMP change analysis using offshore data include: (1) documentation of contraction of the San Francisco ebb-tidal delta at the mouth of San Francisco Bay, which may be associated with sand mining in San Francisco Bay and is probably linked to ongoing persistent coastal erosion (Dallas and Barnard, 2011); (2) an investigation of covering and uncovering of productive rocky nearshore habitats in northern Monterey Bay (Fig. 3; Storlazzi et al., 2011); and (3) analysis of geomorphic change and processes in upper Monterey Canyon (Smith et al., 2005, 2007). Future time-series studies of coastal and marine geomorphology, including post-tsunami analysis (see 4.5, above), will incorporate CSCMP geospatial maps and datasets as authoritative high-resolution baselines.

4.8 Input to models of sediment transport, coastal erosion, and flooding

Models of sediment transport are fundamental to understanding and forecasting coastal erosion, a significant problem along California's ecologically and economically valuable coast. CSCMP high-resolution bathymetric and topographic data are essential input to the CoSMoS model (Barnard et al., 2014), which makes detailed (meter scale) predictions of storm and sea-level-rise induced coastal flooding, erosion, and cliff failures over large geographic scales (100s of kilometers). High-resolution bathymetry also provides a foundational dataset for sediment transport investigations and models, highlighted by recent work in the Santa Barbara Channel (Barnard et al., 2009) and at the mouth of San Francisco Bay (e.g., Barnard et al., 2011; 2012; 2013a; Elias and Hansen, 2013; Hansen et al., 2013). Work in the San Francisco region, connecting bathymetry and sediment transport between the open ocean and San Francisco Bay was included in a Special Volume of Marine Geology entitled, "A multi-disciplinary approach for understanding sediment transport and geomorphic evolution in an estuarine-coastal system—San Francisco Bay" (Barnard et al., 2013b). On the broader scale, George et al. (2015) used CSCMP merge bathymetric and topographic data, geologic maps, and other data to classify headlands along the entire California coast, as part of an effort to advance understanding of headland dynamics, sediment transport, and littoral cell boundaries.

Onshore-offshore geologic maps (Fig. 2, sheet 10) contribute to understanding and modeling coastal erosion by documenting the physical properties (and hence erodibility) of onshore coastal bluffs. Geologic units along the California coast range from highly resistant Mesozoic granitic bedrock (e.g., at Bodega Head, Fig. 2) to relatively unconsolidated and highly erodible, rapidly uplifting Pliocene and Pleistocene sediments north of Pacifica (Edwards et al., 2014) and along the eastern Santa Barbara Channel (Johnson et al., 2013). Offshore coastal sediment can provide a buffer to erosion, and areas with minimal offshore sediment commonly align with areas of more acute coastal erosion. Hence maps of sediment distribution and thickness (e.g., Fig. 2, sheet 9; Fig. 8) also provide important data and insights for understanding and modeling coastal erosion.

4.9 Regional sediment management

California's beaches are presently undergoing significant coastal erosion, a trend expected to increase substantially with ongoing and accelerating sea-level rise. Beach nourishment with sand derived from the adjacent offshore shelf, is one important method of at least temporarily mitigating beach erosion. This practice is widespread in Europe and along the U.S. Atlantic and Gulf of Mexico coasts (Morton et al., 2004; Himmelstoss et al., 2010), and is increasing in California (California Boating and Waterways, 2016). To provide guidance for this issue, the California Sediment Management Workgroup (CSMW) was established as a partnership of federal and state agencies led by the U.S. Army Corps of Engineers and the California National Resources Agency. CSMW is tasked with developing Regional Sediment Management Plans (see below), for which identification of offshore sediment as potential sources for beach nourishment sand is one of many important components. The only detailed comprehensive and consistent maps and digital datasets for offshore sediment distribution and thickness in California are those being developed for CSCMP (e.g., Fig. 2, sheet 9). Published CSCMP maps based on high-resolution seismic-reflection profiling (e.g., Fig. 6c) show tremendous variability in the distribution of unconsolidated sediment, with thicknesses ranging from 0 to 60 m. Primary controls outlined on the maps include proximity to sediment sources, active tectonics (e.g., zones of rapid subsidence adjacent to faults, Fig. 6C), shelf geomorphology, littoral zone and shelf sediment transport, and oceanographic processes.

Regional sediment management plans developed for the southern Monterey Bay and Santa Cruz littoral cells (Fig. 8) provide examples of the need for sediment distribution and thickness maps and data. The Southern Monterey Bay Littoral Cell plan (Phillip Williams and Associates, 2008), which covers the geographic area having the highest coastal erosion rates in California (Hapke et al., 2006), was completed before CSCMP maps and data were available. This plan identified, considered, and developed cost-benefit analyses for three potential offshore sand sources for beach nourishment: (1) the Monterey submarine canyon, requiring sediment interception by new breakwaters or excavation and dredging of offshore sediment-trapping pits; (2) a zone of sand offshore of Sand City, and (3) a nearshore relict sand corridor. Options (2) and (3) are in areas where CSCMP maps show sediment is missing or there is relatively thin (< 2 m) sediment cover amidst scour depressions suggesting very active sediment transport. Because CSCMP maps and data were not available, the Southern Monterey Bay Littoral Cell Plan was not aware of and thus did not acknowledge an enormous sediment mass centered 1,400 m offshore of the mouth of the Salinas River (Fig, 8). This deltaic sediment body is as much as 32 m thick and has an estimated volume of more than 1 $x10^9 m^3$. If and when beach nourishment from offshore sources is considered for this littoral cell, this thick deltaic deposit will be, by far, the most practical option.

In contrast, the Santa Cruz Littoral Cell (Half Moon Bay to Moss Landing) Regional Sediment Management Plan (U.S Army Corps of Engineers et al., 2015) was completed when CSCMP sediment distribution and thickness data (Fig. 8) were available, and these data were used to accurately describe limited potential offshore sediment sources. The geology maps and descriptions that accompany the CSCMP publications for this littoral cell (Cochrane et al., 2015, 2016a, b) make an additional important point, clarifying that many of the thicker offshore sediment accumulations in this littoral cell consist of or are capped by mud deposits, and thus cannot be considered as viable potential sources of beach sand.

4.10 Understanding coastal aquifers

California has been suffering through a significant statewide drought since 2012, mitigated by average winter rainfall in northern California in 2016 and above average rainfall in early 2017. Large parts of California continue to suffer water shortages and substantial restrictions on water use, and groundwater resources are being notably depleted. In this context, understanding groundwater resources is of paramount importance for water management, especially coastal aquifers that have experienced, or are threatened by, saltwater intrusion. Two such coastal aquifers occur in areas covered by CSCMP map publications (Figs. 1, 8). Saltwater intrusion in the Salinas River and Pajaro River valleys of Monterey and Santa Cruz counties has extended as far as 11 km inland (Hanson, 2003; Monterey County Water Resources Agency, 2016), and as far as 5 km inland beneath the Oxnard coastal plain in Ventura County (Izbicki et al., 1996). Hanson et al. (2009, p. 345) point out that: *"Groundwater and surface-water flow are controlled, in part, by the geologic setting. The physiographic province and related tectonic fabric control the relation between the direction of geomorphic features and the flow of water. Geologic structures such as faults and folds control the direction of flow and connectivity of* *groundwater flow. The layering of sediments and their structural association can also influence pathways of groundwater flow and seawater intrusion. Submarine canyons control the shortest potential flow paths that can result in seawater intrusion. The location and extent of offshore outcrops can also affect the flow of groundwater and the potential for seawater intrusion and land subsidence in coastal aquifer systems."*

Both of the offshore regions discussed above are notably faulted and folded, contain thick Quaternary sediments, and are traversed by major submarine canyons that extend landward to within 100 m of the shoreline. Seismic-reflection profiles (e.g., Fig. 6c) collected in these offshore regions for CSCMP provide the offshore geology and structure of these coastal aquifers, providing the important high-resolution stratigraphic framework needed for integrated onshore-offshore modeling. R.T. Hanson (written commun., 2016) will be using the new CSCMP offshore geology and geophysics for a new study of groundwater in the Salinas River valley for Monterey County, and CSCMP maps and data (where available) will have similar value for future work in California's other coastal aquifers.

4.11 Providing geospatial data for emergency response

CSCMP can be helpful in emergency response situations by providing rapid comprehensive, easily accessible geospatial data. For example, shortly after the May 19, 2015 Refugio Beach oil spill (approximately 20,000 gallons were spilled into the ocean), NOAA Environmental Response Management Applications incorporated CSCMP data layers from the USGS data catalog (Golden, 2016) into its web-based Geographic Information System (GIS) to assist both emergency responders and environmental resource managers (National Oceanic and Atmospheric Administration, 2015). Having these data easily available through web services was cited as especially important for users.

5. Importance of Partnerships

Data acquisition, processing, analysis, and publication have all been aided by contributions from a diverse group of stakeholders beyond OPC, NOAA Office of Coast Survey, and USGS. Within California State government, CSCMP was originally planned and supported by the California Coastal Conservancy. California Department of Fish and Wildlife supported substantial ground-truthing data acquisition in central California. The California Geological

Survey has compiled the onland geology for the seamless offshore-onshore geology-geomorphology maps (e.g., Fig. 2, Sheet 10) in the CSCMP publications.

The California State University at Monterey Bay Seafloor Mapping Lab conducted extensive multibeam bathymetry and backscatter mapping, an activity that included substantial student involvement and training. The Center for Habitat Studies at Moss Landing Marine Laboratories (also a California State University campus) has the lead in developing Potential Habitat maps (e.g., Fig. 2, Sheet 7) in the map and data publication series.

CSCMP used bathymetric data collected by the Monterey Bay Aquarium Research Institute in its publications for Monterey Canyon and the Santa Barbara Channel. PG&E supported collection of new bathymetric and seismic-reflection data offshore of the Diablo Canyon Nuclear Power Plant in central California (Fig. 4), and these data were donated to the CSCMP effort.

Within NOAA, in addition to the Office of Coast Survey contributions discussed above, the Office for Coastal Management helped organize a CSCMP workshop and coordinate a CSCMP Steering Committee (see below). National Marine Fisheries staff served as biological experts on USGS ground-truth surveys. National Marine Sanctuaries provided valuable ship time. National Centers for Environmental Information (includes the former National Geophysical Data Center) archives significant CSCMP data.

Also on the federal side, bathymetric lidar data collected by the U.S. Army Corps of Engineers (where available) has been invaluable in partially filling in the 0 to 10 m depth gap on bathymetry maps (e.g., Fig. 2, sheets 1 and 2). The Bureau of Ocean Energy Management (formerly Minerals Management Service) supported USGS acquisition of some bathymetric and ground-truth data in the Santa Barbara Channel. The National Park Service supported development of Potential Habitat maps for the Golden Gate National Recreational Area that were updated and incorporated into CSCMP publications.

Since March, 2015, the CSCMP effort has benefitted from a Steering Committee comprised of representatives from OPC, California Department of Fish and Wildlife, California Coastal Conservancy, California Geological Survey, California Coastal Commission, California State Lands Commission, San Francisco Bay Conservation and Development Commission, USGS, Bureau of Ocean Energy Management, U.S. Navy, U.S. Army Corps of Engineers, NOAA National Marine Sanctuaries, NOAA Office for Coastal Management, NOAA National

Marine Fisheries, and the Federal Emergency Management Agency. The role of the Steering Committee has been to (1) develop a plan for future acquisition of mapping data; (2) provide understanding of how the mapping and derived products are being used by each agency; (3) develop a vision for the next 5-10 years of the program, including how to prioritize work given competing demands on resources; and (4) identify new potential funding sources.

In summary, CSCMP success and accomplishments have been derived from significant partnerships and leveraged contributions of financial, human, and physical resources. This broad group of partners shares the common goal of development and sharing of bathymetric, habitat, and geologic maps and data to support public safety and stewardship of California's State Waters and coastal environment.

6. Outreach

CSCMP maps and data are valuable to the ocean and coastal management community only to the extent that they are being used. The first several years of work and about 95 percent of funding were dominated by data acquisition, and it was not until late 2014, when a significant number of products and publications became available, that outreach efforts became a high priority. In October 2014, the USGS, OPC, and NOAA (Office for Coastal Management) co-hosted two CSCMP workshops at the USGS Pacific Coastal and Marine Science Center in Santa Cruz. Approximately 45 to 50 participants attended each workshop, with representation from 32 different entities including 9 state agencies, 8 federal agencies, 5 academic or research institutions, 3 regional associations, 3 non-governmental organizations, and 7 private-sector companies. These workshops provided the CSCMP workforce with the opportunity to present an update on all that has been accomplished, and to receive important feedback on how CSCMP should proceed in the future to best fit diverse stakeholder needs. The breadth of interests and expertise in the room led to some enthusiastic and stimulating discussions. Some of the more salient points recorded, include:

- *There is interest in new data collection and products to fill in bathymetric, habitat, and geologic mapping of the nearshore (0 to 10 m depth) and to extend coverage into offshore federal waters.* Ecosystems, hazards, and management needs are not restricted to State Waters.
- *Future discussions should focus on identifying gaps, priorities and trade offs.* Coastal

management and planning priorities should guide data acquisition and map and data development priorities. Coordination of data collection and dataset development is essential.

- *Efforts to provide maps and data in suitable digital formats must continue.* Given rapid technology change, this must be an ongoing effort. Making data available through web services (see above) is a good example of adding a relatively new technology to enhance data access.
- *There is a need to build capacity to access and interpret maps and data, and to develop decision-support tools from mapping data.* Decision makers at all levels must be educated on how to access and use map and geospatial data products. Science communication and translation are essential.
- *Mapping products and data have a very large range of applications and are essential for establishing baselines and monitoring change.* This will be especially important as climate warms and sea level rises.
- *Exploring and developing new partnerships should remain a priority.* This applies to all aspects of CSCMP, including data acquisition, map and data development and delivery, data science, information management, education and outreach.

The CSCMP Steering Committee (see 5 above) was established after the workshops. The USGS then provided Steering Committee agencies with webinars describing CSCMP maps and data, and 3 to 5 representatives from each agency were selected to participate in an end-user survey to better understand (1) if and how agencies are using the mapping products; and (2) if there are ways that CSCMP can remove access barriers. Out of 36 selected agency representatives, about 63 percent were already using CSCMP products; unfamiliarity with CSCMP products was the biggest reason cited for no prior use. Other barriers included the need for training and (or) appropriate computing infrastructure, and the local lack of data in shallow water (0 to 10 m, where bathymetric lidar coverage is incomplete) and farther offshore in federal waters. Subsequently, Steering Committee member agencies were also formally surveyed on their geographic preferences for future data acquisition and map and data publications.

The CSCMP outreach effort has also included four press releases that led to interviews and coverage in newspapers, and on the radio and television. Numerous CSCMP lectures and talks have also been delivered to professional societies, academic audiences, service groups, and the general public.

To assess the effectiveness of USGS map/data dissemination efforts and outreach, we obtained web statistics for 21 map and data publications and the data catalog following the most recent (March 29, 2016) press release (four more recent publications could not be queried). For the 25-day period between April 1 and April 25 (17 week days and 8 weekend days), about 70.8 GB of maps and data were transferred, an average of 2.831 GB/day. The four most recent internet publications, announced in the press release, generated about 44 percent of data transfers during the delineated time period; the 17 previous publications, which had been available on-line for 16 to 44 months, generated 56 percent of the data transfers. Data were transferred for about 110 map sheets per day, in the proportions shown on Figure 9.

6. Summary

This report provides an important case history of the development of one of the world's largest and most comprehensive seafloor and coastal mapping databases. Comprehensive map and data publications highlighting bathymetry, backscatter, habitats, and geology, are now complete for about thirty two percent of California's State Waters and are available in multiple digital formats. CSCMP products have been and will be used for a large number of resource management, assessment, and multidisciplinary research applications. Success has been achieved through leveraging of resources and large-scale collaborations between federal, state, academic, and private-sector partners.

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Figure captions

Figure 1. Map of California, with red squares showing California Coastal and Seafloor Mapping Program map areas. Gray squares show the map areas (Salt Point to Monterey, Santa Barbara Channel) for which comprehensive map and datasets have been published (e.g., Fig. 2).

Figure 2. The ten map sheets (1 through 10) for the Offshore of Bodega Head map area (Fig. 1), available in pdf format (Johnson et al., 2015a) at the U.S. Geological Survey (2016) CSCMP website. Maps on sheets 1, 2, 3, 5, 7, and 10 are at 1:24,000 scale. Each publication includes an explanatory pamphlet and a catalog of GIS data layers with web services. At present, twenty five of these map publications have been completed, covering about thirty two percent of California's mainland coast.

Figure 3. Small areas of (a) the Seafloor Character Map (sheet 5) and (b) the Potential Habitats Map (sheet 7) from the Offshore of Santa Cruz map area (Fig. 1; Cochrane et al., 2016a), highlighting the diversity of seafloor habitats in California's State Waters. RSDs are rippled scour depressions (see text for discussion). *SLR* is San Lorenzo River.

Figure 4. Maps of central California coast offshore of offshore of Point Buchon (Fig. 1; PB), the Diablo Canyon Power Plant (DC), and Point San Luis (PS). Map (a) shows shaded relief bathymetry (contour interval of 10 m). Map (b) is offshore geology from Watt and others (2015), highlighting active faults (HF, Hosgri fault; PBF, Point Buchon fault; SF, Shoreline fault). CSCMP high-resolution bathymetry and seismic-reflection profiling provided the data for new fault characterization (e.g., Johnson and Watt, 2012; Johnson et al., 2014) and improved earthquake hazard assessments.

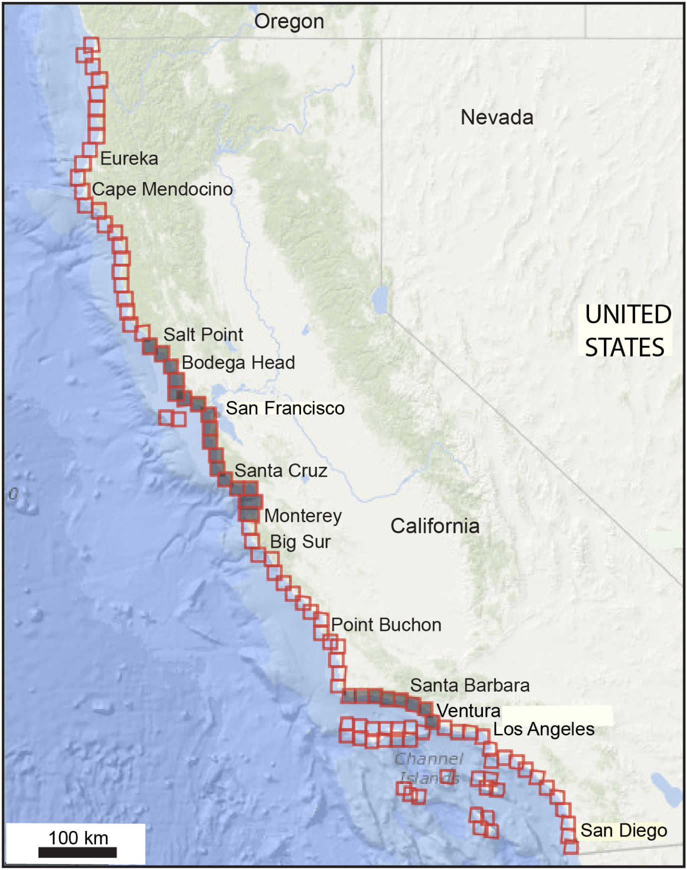
Figure 5. Hillshade DEM's showing submarine landslides and sites of potential future landslides along the steep upper continental slope in the western (a) and eastern (b) Santa Barbara Channel area (Fig. 1). EC, El Capitan; G, Gaviota; Go, Goleta; PH, Platform Holly. Contours are in meters. See text for discussion.

Figure 6**. (a)**. Hillshade DEM showing debris-flow lobes and chutes on the relatively flat (~1°) continental shelf between Bodega Head and Fort Ross in northern California. **(b)**. Geologic map of the same area, showing location of the San Andreas fault zone. On (a) and (b), purple line is offshore limit of State Waters, blue line is shoreline, green line is location of seismic-reflection profile shown in (c), and contours are in meters. Offshore geologic units in (b) include: br, Mesozoic bedrock; Qms, sandy marine sediment; Qmsd, rippled scour depressions; Qmsf, muddy marine sediment; Qmsl, marine sediment lobes. **(c)** Seismic-reflection profile showing unconsolidated sediment layer (blue shading), faults (red dashed lines), erosional unconformity on bedrock (purple dashed line), some gently dipping reflections (green lines), and seafloor multiple (echo of seafloor reflector, yellow dashed line). Such profiles are used to map offshore faults, sediment distribution and thickness, submarine landslides and potentially unstable seafloor, coastal aquifers, gas-saturated subsurface zones, and other geologic phenomena. Figures are from the Offshore of Bodega Head map area (Fig. 2) and the Offshore of Fort Ross map area (Johnson et al., 2015a, b).

Figure 7. Shaded-relief bathymetry showing the outer shelf and upper slope south of Goleta, crossed by the South Ellwood anticline (SEA) and South Ellwood syncline (SES). White dashed line shows shelfbreak at depth of ~90 m. Black dotted line shows area of proposed lease adjustment. The rough surface texture on unit Tbu (brown shading, undivided Miocene to Pliocene Monterey, Siquoc, and Pico Formations) results from differentially eroded sediment layers and from "hydrocarbon-induced topography," which can include seeps, asphalt mounds (a), carbonate mats, mud volcanos, pockmarks, mounds, and other features (Keller et al., 2007). Unit Qmp (blue shading) represents individual or large groupings of dense pockmarks, including the large occurrence south of shelfbreak on the upper slope. Qms is Quaternary marine sediment. Mapping from Conrad et al. (2014). Location shown in Figure 5; yellow line is boundary of California State Waters.

Figure 8. Map, based on Map D on sheet 9 in Cochrane et al. (2015, 2016a, b); Dartnell et al. (2016); and Johnson et al. (2016), showing distribution and thickness of latest Pleistocene to Holocene sediment in the southern part of the Santa Cruz littoral cell (SCLC) and the southern Monterey Bay littoral cell (SMBLC), which are divided by the submarine Monterey Canyon system (includes Soquel Canyon). Mapping is based on contouring values derived from seismic-reflection profiles, but data are insufficient to map sediment within the extremely variable submarine-canyon environment. Note the thick deltaic sediment offshore of the mouth of the Salinas River (*SaR*). The thicker sediment accumulations offshore of Santa Cruz (SC) and Davenport (D) occur within a mud belt and are thus poorly suited for potential beach nourishment. Other abbreviations: M, Monterey; ML, Moss Landing; PR, Pajaro River; S, Sand City; SaR, SR, San Lorenzo River; WC, Waddell Creek. Yellow line is outer limit of California State Waters; blue line is the shoreline.

Figure 9. Chart showing proportions of CSCMP data transfers per map sheets, derived from web statistics compiled in April, 2016.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Channel Islands
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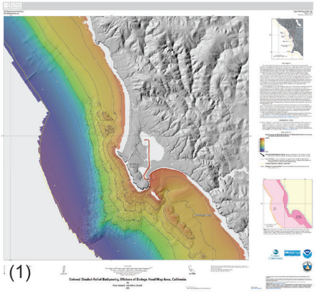
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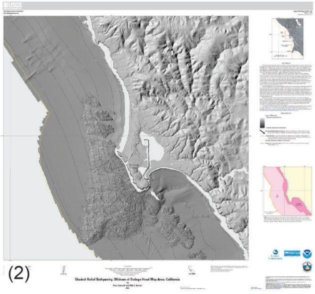
Colored Shaded-Relief Bathymetry, Offshore of Bodega Head Map Area, California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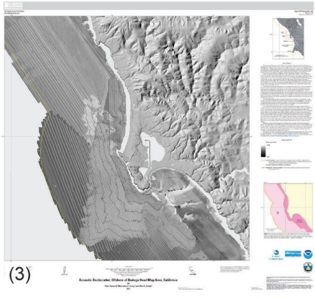
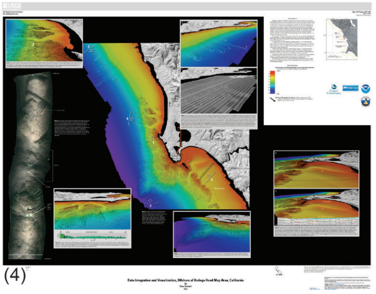
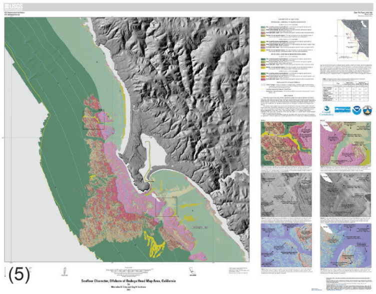
Shaded-Relief Bathymetry, Offshore of Bodega Head Map Area, California


(3)

Acoustic Backscatter, Offshore of Bodega Head Map Area, California


(4)

Data Integration and Visualization, Offshore of Bodega Head Map Area, California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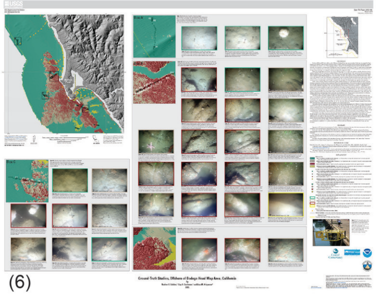
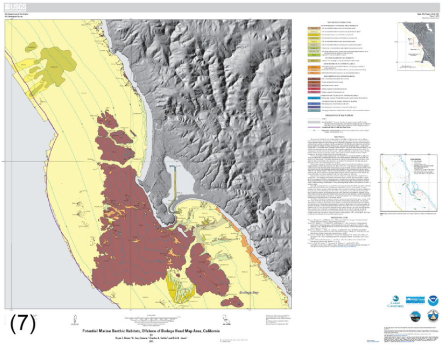
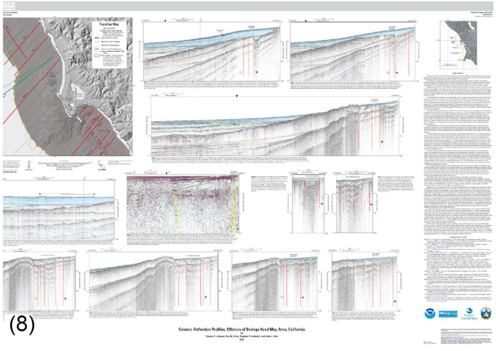
Seafloor Character, Offshore of Bodega Head Map Area, California


(6)

Ground-Truth Studies, Offshore of Bodega Head Map Area, California


(7)
Potential Marine Benthic Habitats, Offshore of Bodega Head Map Area, California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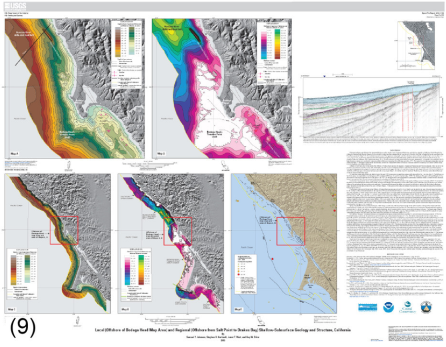
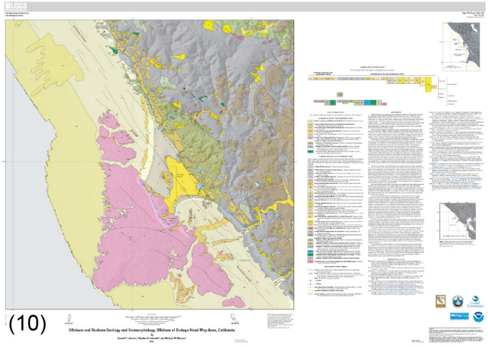
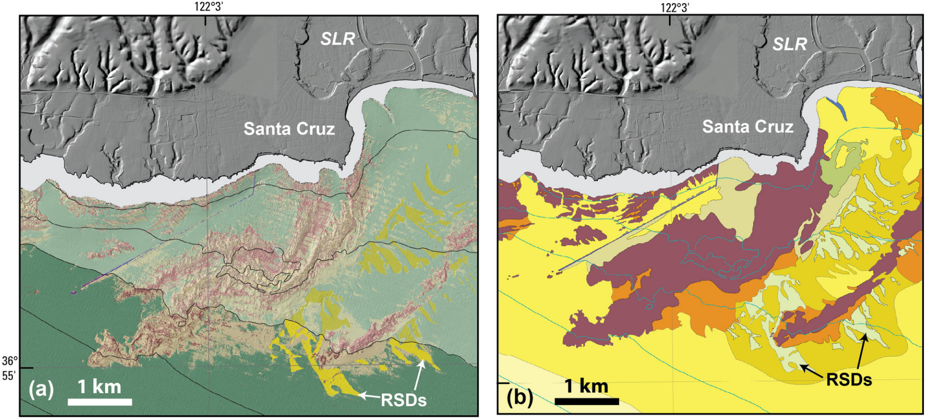
Seismic-Reflection Profiles, Offshore of Bodega Head Map Area, California


(9)
Local (Offshore of Bodega Head Map Area) and Regional (Offshore from Salt Point to Drakes Bay) Shallow-Subsurface Geology and Structure, California


(10)
Offshore and Onshore Geology and Geomorphology, Offshore of Bodega Head Map Area, California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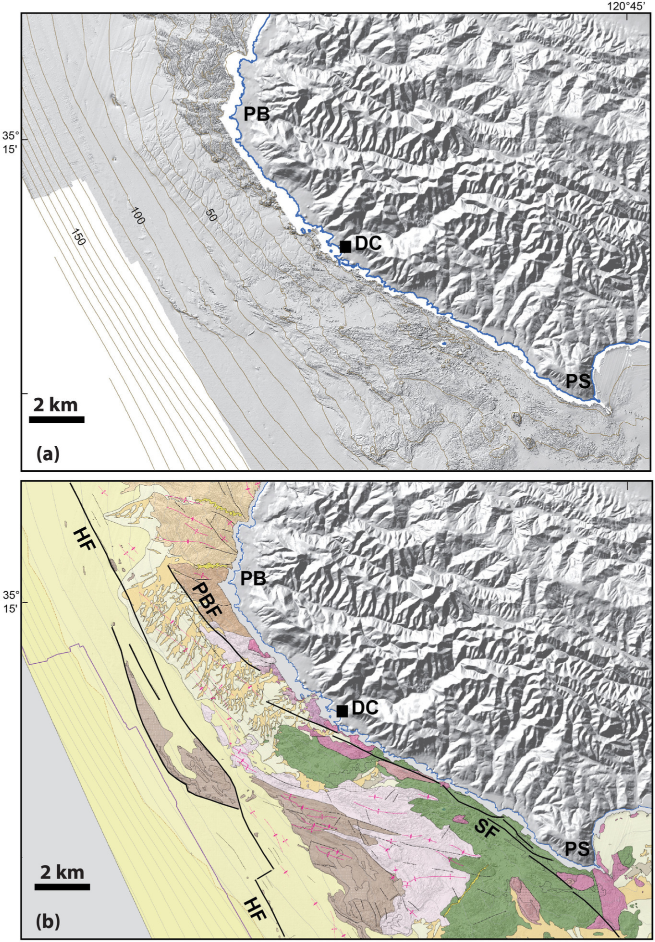
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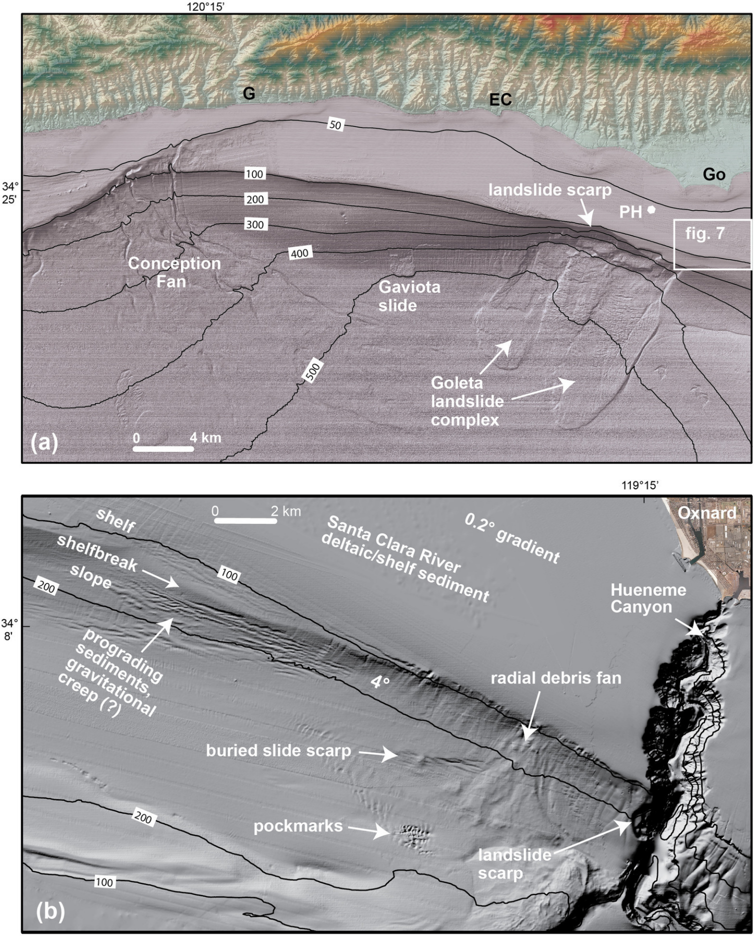
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landslide
complex
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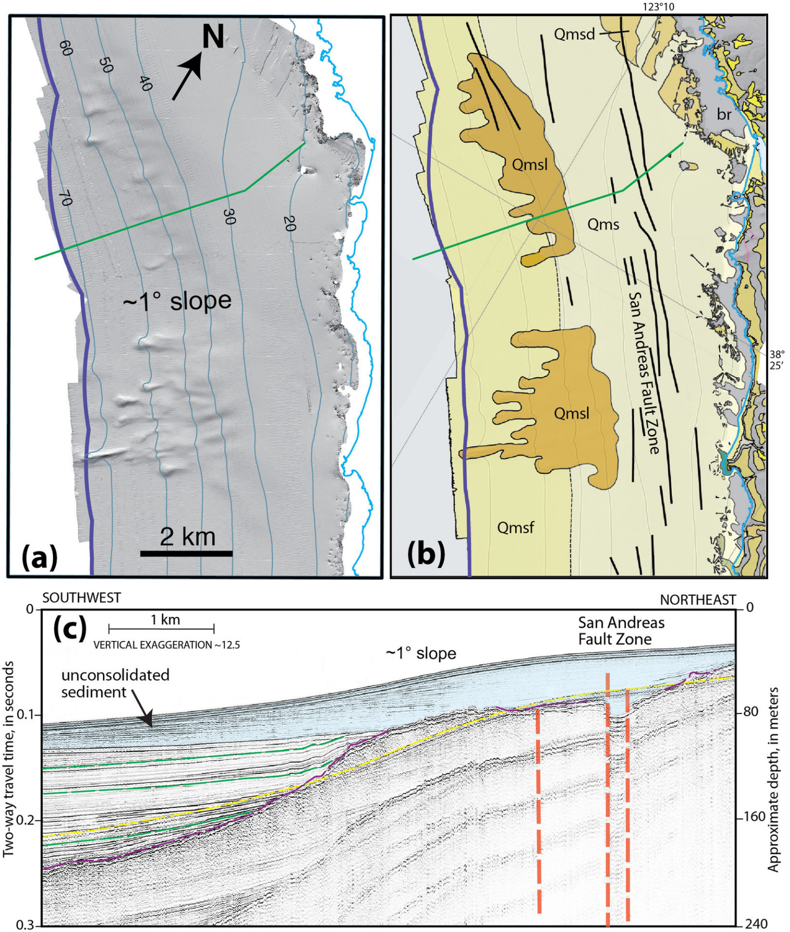
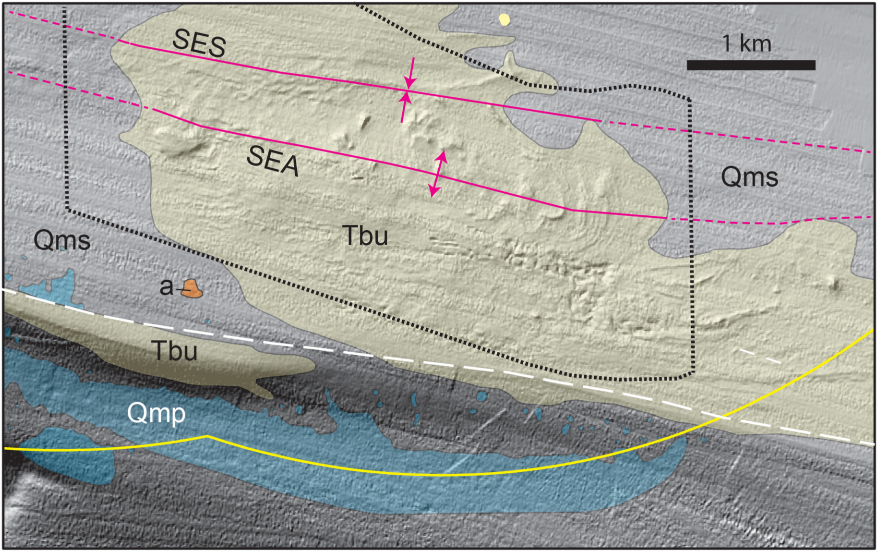
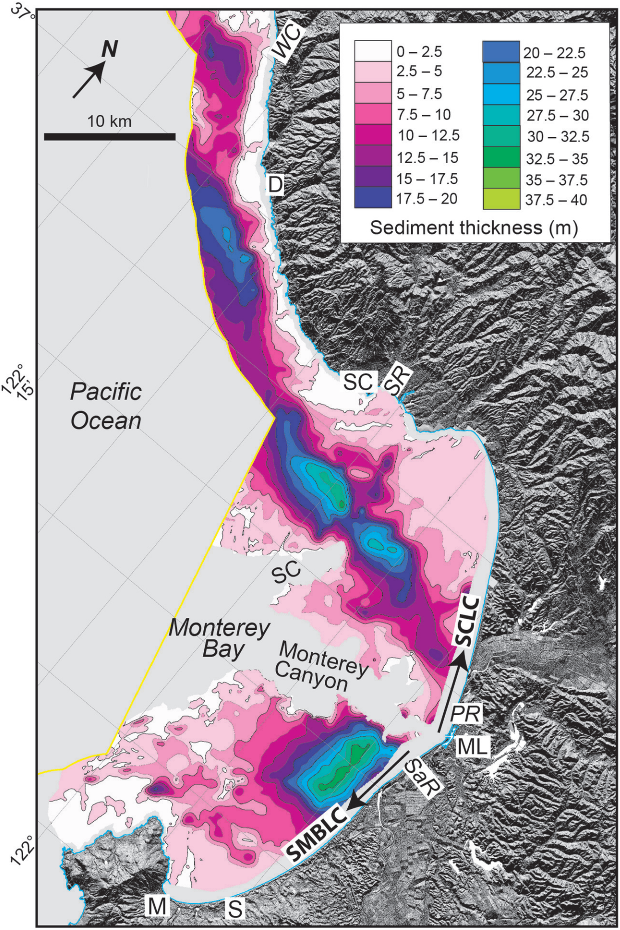
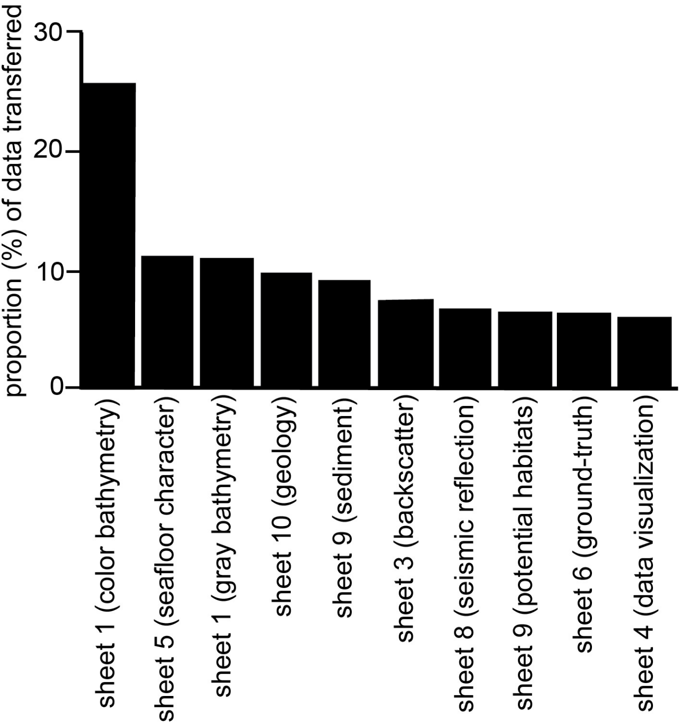
4 km
119°15'
Oxnard
0
2 km
shelf
shelfbreak
slope
100
200
Santa Clara River
deltaic/shelf sediment
0.2° gradient
Hueneme
Canyon
34°
8'
prograding
sediments,
gravitational
creep (?)
4°
radial debris fan
buried slide scarp
pockmarks
200
landslide
scarp
100
(b)


(a)
N
60
50
40
70
30
20
~1° slope
2 km
(b)
123°10
Qmsd
br
Qmsl
Qms
Qmsl
Qmsf
San Andreas Fault Zone
38° 25′
(c)
SOUTHWEST
NORTHEAST
1 km
VERTICAL EXAGGERATION ~12.5
~1° slope
San Andreas Fault Zone
unconsolidated sediment
Two-way travel time, in seconds
0
0.1
0.2
0.3
Approximate depth, in meters
0
80
160
240


SES
1 km
SEA
Qms
Tbu
Qms
a
Tbu
Qmp


37°
N
10 km
WC
D
0 – 2.5
2.5 – 5
5 – 7.5
7.5 – 10
10 – 12.5
12.5 – 15
15 – 17.5
17.5 – 20
20 – 22.5
22.5 – 25
25 – 27.5
27.5 – 30
30 – 32.5
32.5 – 35
35 – 37.5
37.5 – 40
Sediment thickness (m)
122° 15'
Pacific Ocean
SC
SR
SC
Monterey Bay
Monterey Canyon
SCLC
PR
ML
SaR
SMBLC
122°
M
S



proportion (%) of data transferred
30
20
10
0
sheet 1 (color bathymetry)
sheet 5 (seafloor character)
sheet 1 (gray bathymetry)
sheet 10 (geology)
sheet 9 (sediment)
sheet 3 (backscatter)
sheet 8 (seismic reflection)
sheet 9 (potential habitats)
sheet 6 (ground-truth)
sheet 4 (data visualization)